R&D Proposal for EIC Background Studies and the Impact on the IR and Detector design

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Abstract

In this proposal, we request funding to perform detailed simulations of the EIC machine related backgrounds generated in the interaction region (IR). This will allow evaluation of the background radiation reaching the detectors and front-end electronics. The detectors must be sufficiently well protected to prevent both excessive component occupancies and deterioration from radiation damage. Experience at HERA has shown that synchrotron radiation and beam interactions with residual beamline gas are likely the major sources of background that will require mitigation at the EIC. The rate and the type of background signal impacts the technology choices for the central and auxiliary detectors. There is an effort at Brookhaven National Lab to study beam gas interactions; however, it is focused on the eRHIC design. We will create independent simulation tools and procedures and a validation method using HERA background data. We will apply this to the JLEIC configuration, but the tools and procedures developed and validated will be of general applicability to any EIC IR design. Knowledge gained will be critical to the machine and detector designs at both JLEIC and eRHIC. Collaboration between the accelerator and detector groups from both laboratories is necessary and will support an iterative design process that maximizes the capabilities of the physics program at an EIC.

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1 Introduction

The EIC machine design directly impacts the quantity and type of radiation reaching detectors in the interaction region, which, in turn, influences both the physics program and the detectors design. Background radiation also greatly affects the systematic uncertainties of the physics measurements. It is important to fully understand and minimize the systematic uncertainty, as it will dominate the high-precision physics measurements at high luminosity. Background radiation is influenced by the arrangement of the magnets which guide the beam, bunch spacing, beam current, and beam optics. Therefore it is critical to perform a thorough study of the type and dose of machine-induced background now, before decisions regarding the interaction region layout are made final. This insight will inform decisions that minimize and mitigate sources of background at the early design phase and will inform detector placement and technology choices as well. Close collaboration between the accelerator and detector efforts is necessary to inform the design process in view of background conditions and maximize the potential of the physics program at the EIC.

Experience at earlier facilities, especially the previous electron-proton collider at HERA at DESY, further motivates a detailed study of the background in the interaction region (IR). HERA-II upgrade planned to increase luminosity by a factor of seven by stronger beam focusing at the interaction points (IP). However, the upgraded machine generated severe levels of background in the interaction region. The primary sources of background were direct synchrotron radiation and beam gas scattering due to vacuum degradation. Ultimately the problems were addressed and the upgrade was a success, increasing luminosity by a factor of five; however, this experience underscores the need to begin studies in an early phase[5][11][12].

Detailed simulations must be performed for relevant background sources. Sources of background observed at other facilities are listed below.

- Synchrotron radiation
- Beam-gas interactions
- Beam halo
- Beam loss
- Neutron flux
- Elastic eA scattering and eA bremsstrahlung

Neutrons with energies around a few hundred keV can be detrimental to detector components. For instance, silicon photo-multiplier tubes are especially vulnerable. A quantitative estimate of the neutron flux is needed for detector development and placement. To achieve this, modeling the full neutron thermalization from beam-gas events in the experimental hall is a possible future extension to this study.

The focus of the first two years of this proposal is on the synchrotron radiation and beam-gas interactions.

2 Goals of the proposal

We propose a study to determine the quantity, type, and distribution of machine-induced background generated in the interaction region (IR). The following is a brief summary of the scope of effort of this proposal:

- Synchrotron radiation (SR): This is a potentially large source of random hits in the tracking detectors. This also deposits several kilowatts of power into the beam pipe in the central detector region, which must then be cooled. Synchrotron radiation is also a direct and indirect source of background in the Compton polarimeter, the luminosity monitor, and low-Q^2 tagger located on the downstream electron side of the IR. An initial design of the central beam pipe from JLEIC exists, including synchrotron radiation collimation. Through out-gassing of the beam pipe, synchrotron radiation can also be the primary source of vacuum degradation near the IR

- Beam gas interactions of the incident ion beam with the residual vacuum: Ion-beam gas interactions are the dominant source of high energy background in the central detector at HERA, and may be an important source of neutrons that thermalize within the detector hall. In the first year, we will study the beam-gas interactions in the central region (between the upstream and downstream ion final focus quadrupole). In the second year, if resources permit, we will extend this study to the full ± 40 m interaction region.
- Vacuum dynamics: In the first year, we will use a model assumption for the vacuum profile in the IR. In the second year, we will use the results of the synchrotron radiation study, the beam pipe design, and initial pumping stations to explicitly model the vacuum profile throughout the IR. This will be used to iterate the beam pipe design and the beam-gas study.

Synchrotron radiation and beam-gas background rates are related through desorption from the beam pipe wall and other surfaces caused by SR (dynamic vacuum). This component of the beam-gas background caused by the dynamic vacuum was responsible for a large part of the problems at HERA-II. Both SR and the resulting desorption are unlikely to be adequately simulated by GEANT4 alone. We intend to use a standalone SR program developed and used at PEP as well as specialized programs Molflow+ (vacuum simulation from beam pipe geometry and pumping speed) and Synrad+ (desorption due to SR) in conjunction with GEANT4 (GEMC) to simulate the relationship between SR, vacuum, and beam-gas rates. The results can be compared to, and checked against, HERA data that show the change of the beam-gas rates as the dynamic vacuum in the HERA interaction region gradually improved with scrubbing from the electron beam.

3 JLEIC machine and interaction region parameters

3.1 Jefferson Lab Electron-Ion Collider

Jefferson Lab Electron-Ion Collider (JLEIC) is designed as a conventional ring-ring collider [2]. Its high luminosity performance exceeding 10^{34} cm^{-2}s^{-1} at each interaction point is based on high repetition rate, strong focusing at the collision points, and low beam emittances. The figure-8 design maintains high polarization of both the electron and ion beams and allows for efficient polarization control [7]. Table 1 summarizes some of the design parameters for the machine. While thorough background studies must be completed to determine the specific parameters of the machine, the background issues to be studied in this project are common to any EIC design and the tools and techniques that will be developed in this project will be applicable to and allow benchmarking of other EIC designs.

Table 1: An example of JLEIC design parameters.

CM energy	GeV	44.7 (medium)	
		p	e
Beam energy	GeV	100	5
Collision frequency	MHz	476	
Particles per bunch	10^{10}	0.98	3.7
Beam current	A	0.75	2.82
Polarization	%	>80	>80
Bunch length, rms	cm	1	1
Norm. emittance, x/y	μm	0.5/0.1	54/10.8
x/y β^*	cm	6/1.2	5.1/1.0
Vert. beam-beam param.		0.015	0.068
Laslett tune shift		0.055	6×10^{-4}
Detector space, up/down	m	3.6/7	3.2/3
Hourglass (HG) reduction		0.87	
Lumi./IP, w/ HG, 10^{33}	cm^{-2} s^{-1}	21.4	

3.2 Total acceptance detector

As illustrated in Fig. 1, accessing the EIC physics requires reconstruction of all final state particles in each event. A particular challenge is the detection of final state particles associated with the initial ion that form small angles with respect to the ion beam. The small-angle particles pass through the nearest machine elements,and enter a far forward spectrometer that extends +40m.

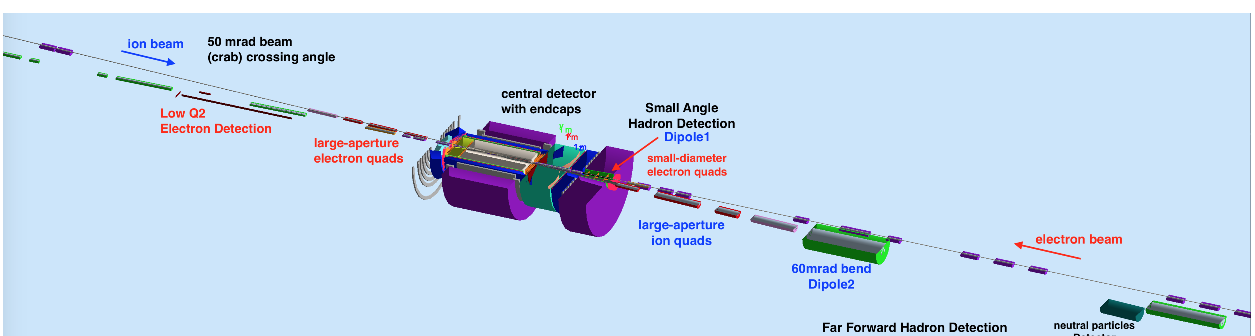

Figure 1: JLEIC Total acceptance detector concept.

The central detector includes a 4 m long solenoid extending 2.4 m on the outgoing ion side and 1.6 m on the opposite side. The electron beam is aligned with the detector axis to avoid generation of synchrotron radiation. The ion beam crosses the electron beam at a relatively large angle of 50 mrad and provides fast separation of the two beams, enabling excellent acceptance in the far forward direction.

The detector has a sufficiently large magnet-free space near the interaction point for detection of particles down to about 0.5° in front of the final focus quadrupoles. Particles scattered between 0° − 0.5° pass through large-aperture final focusing quadrupoles, are momentum-analyzed by a spectrometer dipole, and are detected at the momentum-dependent secondary focus [1] [2] [8] [9] [10] further downstream (up to 42 m).

3.3 Interaction region and beam pipe

The JLEIC beam pipe concept in the IR incorporates several design features to balance the sometimes competing requirements. Particular issues include:

- Minimize multiple scattering for all final state particles as they exit the vacuum
- Smooth transitions to minimize beam wakefield effects and maximize pumping conductance
- Apertures consistent with the Beam Stay Clear (BSC) of $10\sigma_{x,y} + 0.5$ cm (including during injection)
- Synchrotron radiation mask (minimal aperture) between the interaction point and the last upstream electron quadrupole
- Maximal aperture to allow synchrotron radiation to pass freely through the central region
- Minimal inner radius of the vertex tracker

The present design is illustrated in Figs. 2, 3. The design is such that almost all final state particles transit the beryllium beam pipe or windows out of the beam pipe at tangential angles greater than 100 mrad.

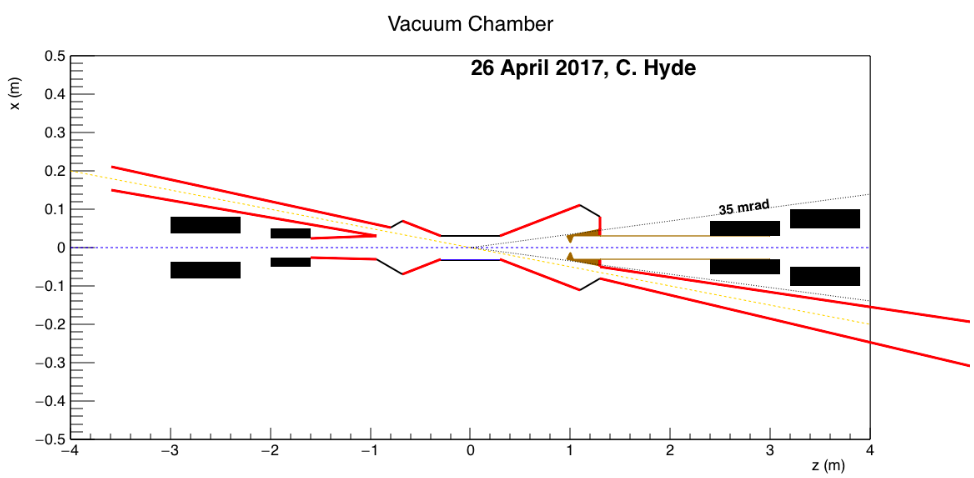

Figure 2: Two-dimensional schematic of the JLEIC interaction region beam pipe design. The electron beam travels in the minus z direction. The ion beam enters from upper left, at −50 mrad in the $z \times x$ plane. Note that the x and z scales are not equal. The black rectangles illustrate the first two upstream and downstream electron final focus quads (FFQ). The thin black regions of the beam pipe indicates regions where detectable particles exit the vacuum. The ion downstream ion conical pipe extends through the first dipole and matches the acceptance of the downstream ion FFQ triplet. The central straight section is a two-layered, water-cooled Beryllium pipe, matching the PEP-II design.

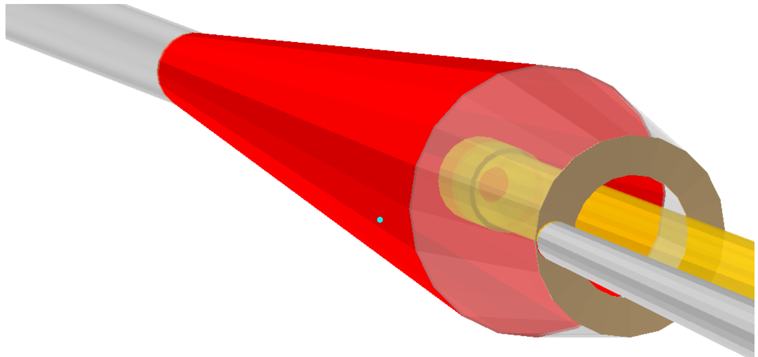

Figure 3: Three-dimensional zoom of the ion-downstream side of the JLEIC interaction region beam pipe design. The colors simply distinguish separate components. The conical flare and taper extends to $z = 1.3$ m. This pipe is illustrated semi-transparent to view the electron beam pipe, which extends into the vacuum and at $z = 1$ m tapers to a 1.2 cm radius copper synchrotron radiation shield.

4 Software tools

4.1 GEMC

GEMC, short for GEANT4 Monte Carlo, is the simulation software based on GEANT4 used by both CLAS12 and the JLEIC effort to study how particles interact with the components of the beam line and detector. It is capable of tracking particles through any material and recording interactions and detector response at every step. Built in C++, the software permits users to build the elements of the experiment using either Perl scripts or by importing designs directly from CAD. GEMC permits users to model a particle beam with great specificity. One can specify the point of origin, particle species, momentum, and direction. Additional options permit a spatial spread in θ and ϕ values, Gaussian beam profile, and bunch spacing. For the beam-gas studies, the beam pipe design in the GEMC model will be filled with residual gas species at the estimated partial-pressures. All beam-gas interactions and their subsequent interactions with the detector elements will be modeled in GEANT4.

Alternatively, users may import generated events for simulation using the LUND format. Simulation data is recorded in EVIO format, short for Event Input/Output. It is then written to a separate file which can be converted to ROOT for data analysis using a program called Evio2Root[13].

4.2 Initial Distribution Generator

Based on nominal beam dynamics from the accelerator division, a script was written using ROOT that accurately models these parameters. Specifically, it generates an optically matched transverse bunch distribution and writes the data for these particles into a LUND file. The file is then called in GEMC rather than the native beam options.

4.3 Molflow+

Molflow+ is a test-particle Monte Carlo simulation package for ultra-high vacuum systems, developed at CERN. It allows the user to calculate pressure in an arbitrarily complex geometry. The name, a portmanteau of "molecular flow", comes from the condition that the mean free path is much greater than the geometric size of the molecule so that molecular collisions can be ignored. The software permits users to import geometries in CAD format and calculates pressure profiles for ultra-high vacuum systems, taking into account material out-gassing, pumping, and geometry. It was developed in C++ and is currently supported for Windows 10 [6].

4.4 Synrad+

Designed to complement the previous program, Synrad+ tracks photons instead of molecules to determine the flux and power distribution on surfaces caused by synchrotron radiation. Once beam properties are defined, the beam trajectory is calculated from user-defined magnetic regions. From this beam, photons are emitted and their reflectance or absorbance is calculated when they strike surfaces. This information is helpful to the machine design in areas where synchrotron-induced heat or gas desorption matters. The flux distributions calculated in Synrad+ are then used to define a synchrotron radiation dependent desorption map to model the vacuum system in Molflow+[6].

4.5 Synchrotron radiation tools developed at SLAC (SR code)

The FORTRAN program `SYNC_BKG` was originally developed to study final focus quadrupole radiation and has been extended to include bend radiation from the last bend magnets before the IR. `SYNC_BKG` performs a transverse scan of the beam profile and traces fans of radiation generated by weighted sections of the transverse beam scan to various defined beam pipe apertures. The number of photons and the power are tallied for each aperture. This information can then be used by a second FORTRAN program (MASKING) which is an EGS interface program. MASKING can model various elements and compounds to find out how many incident photons are either forward scattered, backscattered, or transmitted through the specified material. The program can save a photon file that is easily read into a GEANT4 model as a background source wherein the detector model can then tally the number of background hits and occupancy of various subdetectors. The programs are generally fast and can quickly adapt to modifications in either the beam pipe design or lattice design allowing for a quick turnaround and rapid convergence to an optimal design. The results from these programs can be compared to Synrad+ output for benchmarking and verification. As stated earlier, the electron beam aspect ratio is quite low for the JLEIC design (5:1). This is significantly lower than any other previous high current storage ring. This low ratio presents unique challenges to the control of SR especially from the final focus elements. The masking must be fairly close to the IP in Z and fairly close to the beam-stay-clear. This SR masking design has the potential to become a source of beam-gas backgrounds in the detector. We anticipate the possibility of needing to iterate the SR masking design against SR backgrounds and beam-gas backgrounds. In addition, the current electron beam will produce high levels of SR throughout the ring lattice as well as in the IR and these photons will strike the beam pipe producing extra out-gassing initially. This 'dynamic' out-gassing will decrease as the amount of stored amp-hours of the electron beam increases. A standard rule of thumb is that at least 100 amp-hrs are necessary before the SR photons have 'scrubbed' the beam pipe enough and the vacuum levels return to similar values found when there is no beam.

5 Tools and procedure validation

To establish the validity of future simulations using current software tools GEMC, GEANT4, and the JLEIC initial distribution generator have been benchmarked against background rates measured at HERA following the luminosity upgrade. By replicating HERA conditions, simulations produced background rates that were comparable to those recorded in at the "C5" background monitor at the ZEUS detector.

In order to benchmark simulation tools against the observed background rates, the ZEUS C5 detector was modeled and positioned at the correct location relative to the IP. A beam pipe with the same specifications as the original HERA beam pipe was filled with a hydrogen target of density corresponding to the vacuum quality of the IP at HERA. The basic HERA configuration was simulated: i.e., a 900 GeV proton beam was fired from the center of the beam pipe in front of the higher density gas region and the detector hits were recorded[3].

The rate of particles in the virtual C5 detector was calculated for HERA parameters. The virtual C5 detector measured approximately 33kHz for charged particle events, which agrees with ZEUS data. Additional studies were made on vacuum density, vacuum region length, physics model, and beam pipe composition[4].

The benchmarking study has confirmed that using HERA parameters, the GEMC software and the initial distribution generator produce data in agreement with the experimental results from HERA. This validates future results produced with these tools and reinforces both the need and readiness to undertake further studies of the beam gas interactions generated in the EIC.

6 Project deliverables

FY2018: First and second quarters:

1. Complete and document the HERA benchmarking studies.
2. Model the current baseline design of JLEIC IR beam pipe concept in GEMC/GEANT4 simulations.
3. Benchmark synchrotron radiation rates produced within GEANT4 and compare with SR code simulations.
4. Develop an interface of the SR code to GEMC.
5. Model the current baseline design of JLEIC IR beam pipe concept in a 3D CAD model.

This is necessary for all forthcoming physics simulations, background studies, support structure design, and vacuum pressure distribution studies.

FY2018: Third and fourth quarters:

1. Determine background rates as a function of vacuum levels for the JLEIC configuration.
2. Determine the intensity and distribution in the beam pipe and in the various detectors using GEMC interfaced with SR code.
3. Interface CAD drawings with Molflow+ and Synrad+.
4. Using validated software tools and result of beam pipe design, evaluate background contributions from hadron beam/gas interactions under nominal vacuum levels. Deliver quantitative analysis of amount and distribution of this background source using EIC parameters. At this stage, vacuum is not yet simulated.

Full funding will enable the completion of all items. At the 80% funding level, items in black and blue text will be achieved. In the case of 60% funding, only the items in black text will be completed.

FY2019:

Use Molflow+ and Synrad+ to realistically simulate vacuum conditions. Initially, this will be for static conditions. Next, the SR level determined in year 1 will be used to be determine the level of dynamic vacuum due to the SR. The vacuum levels thus determined then will be used in GEMC to update the beam gas boundaries. Finally, the result will be compared to the HERA experience.

Funding for this study will enable the completion of many high-impact deliverables. These achievements will be critical milestones for the EIC design process.

7 Budget

The requested funds and also stated allocations are summarized in Table 2. The costs are fully burdened. The bulk of the funds will go to fund the student, partial post-doc, and travel expenses for the consultant from SLAC.

Table 2: Cost breakdown for requested funding

	FY18		
Resources	100% Funding	80% Funding	60% Funding
Post-Doc (JLab)	$25K	$11K	$0K
Student (ODU)	$35K	$35K	$35K
Travel (Consult M.S. from SLAC)	$10K	$10K	$7K
Total	$70K	$56K	$42K

Additionally, the available manpower and contributors to the project are listed below. Work split/assignments:

- Simulations for background: Latifa Elouadrhiri, Christine Ploen (Student) and Kijun Park (Post-doc)
- IR design contact person: Vasiliy Morozov
- Beam pipe design: Charles Hyde
- Synchrotron radiation simulations using SR code: Mike Sullivan
- Vaccum calculation: Marci Stutzman and Kijun Park (Post-doc)
- 3D CAD modeling of JLEIC IR and beam pipe and GEANT4 implementation: Tim Minkowski and Christine Ploen (Student)

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